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STATISTICALLY BASED DECOMPRESSION TABLES X: REAL-TIME DECOMPRESSION ALGORITHM USING A PROBABILISTIC MODEL

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TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

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Underwater decompression meters or computers sense a diver's changes of depth in real-time and calculate a decompression schedule for the individual diver's exposure. Currently available devices compare calculated nitrogen tissue tensions to a set of stored "safe" constants. No explicit quantitative connection between these rules and the risk of decompression sickness has been established. Well calibrated probabilistic models, even though computationally more intense, can be used to specify decompression procedures tailored to control the risk of decompression sickness.

Probabilistic models allow conscious choice of the degree of "safety" or acceptable risk. Previously, the choice required searching up to tens of thousands of possibilities for any given dive. That method cannot be employed in real time without a very fast computer. We describe a quicker search method that depends upon a "recent optimal" solution so that it can be implemented in real time. The real time algorithm compared favorably with decompression schedules obtained by extensive searches. Timing requirements for updating calculations (important for hardware specification) depends on how fast the "recent optimal" answer changes. Risk management for repetitive diving is described in terms of conditional probability. The algorithm can be used to permit the acceptable risk level to vary during real time as the dive severity increases, and to include multiple breathing gases.

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BACKGROUND

Despite much research, the detailed causes of decompression sickness (DCS) remain unknown. In years of trial-and-error and accumulation of experienced judgment, numerous collections of decompression tables have been produced telling a diver the "safe" way to return to the surface (that is, to avoid DCS).

Decompression Tables

Decompression tables are collections of rules specifying pauses, or "stops" at intermediate depths during the return to surface after exposure to a deeper depth. Tables are printed for many (sometimes hundreds) of dive depth and time combinations. But no collection can ever be complete, and standard rules issued with tables normally instruct the diver to choose a conservative table entry, for example, use the deepest depth and the longest dive time before decompression. This conservatism can become very severe for a diver who spends a small fraction of her total time relatively deep. Table inflexibility also is restrictive to a diver who frequently practices "repetitive diving," that is, beginning a new dive while her body is still under the influence of another dive just recently completed. Thus arises the appeal of a flexible decompression meter, or computer, which can "tailor" an "exact" decompression schedule for a diver, regardless of the complexity of her depth/time profile. Devices were developed by many groups, starting in Canada with first analog (1), then digital computers (2), decompression meters or computers.

Deterministic Algorithms

Central to the function of such decompression meters is a mathematical construct (algorithm), which periodically senses the diver's depth, updates a number of calculations and

presents a specific decompression table for the diver. Invariably the calculations include a set of variables frequently referred to as tissue gas tensions. These quantities are of interest because inert gases, such as atmospheric nitrogen, dissolve in body tissues up to a limit determined by atmospheric pressure. When the pressure is reduced, the prior dissolved gas exceeds the new atmospheric limit, termed "gas supersaturation," and has a thermodynamic tendency to form bubbles. The tissue tension calculations have used simple exponential functions (3,4), asymmetric exponential (5), part linear-part exponential (6,7), or a set of differential equations inspired by flow-through certain filters (8). Except for the latter, these computations are relatively easy to program into a meter and fairly rapid for the computer to calculate (9).

In common decompression meters, recommendations to the diver on the next shallower safe stop depth are generally made by comparison of theoretical tissue tensions to a set of stored "safe supersaturation constants." These are sometimes termed ascent criteria or "M values" and are treated as sharp boundaries between "safe" and "unsafe" states. Current meters with these algorithms have many problems, which are discussed in other publications (10-12). A primary problem is an unknown level of safety, i.e., no objective statistical connection between the "M values" and decompression safety data is made. Our present technique corrects this deficiency.

Associated with this theoretical statistical concern is a practical question on the statistics of verification testing. Without a statistical link among different individual dives, testing only establishes the binomial confidence limits on the actual replicated test dives; for example, zero cases in 10 replicated dives establishes, at 95% confidence, that the underlying

incidence on that specific dive is less than about 31% DCS. U.S. Navy testing practice has subjected a minority subset of decompression schedules to modestly replicate testing: 4-6 per schedule for the extensively adopted 1956 Air Decompression Table (13) to 10-20 divers per schedule in more recent work (6,7). A popular civilian diving computer for multilevel and repetitive dives only tested one dive combination with 12 people (14).

Probabilistic models

There is a documented uncertainty in decompression: an identical decompression procedure can cause DCS in some people while others are unaffected, and a person suffering DCS on one occasion can often be free of DCS on other identical exposures. This was most convincingly demonstrated by Gray and colleagues with a set of provocative altitude decompression exposures repeated identically on 5 occasions to a group of test subjects (15). The outcomes were definitely not reproducible. In fact, the data more closely supported a hypothesis of totally random variation. Therefore, the terms "safe" and "unsafe" lose their usefulness, unless one speaks in specific terms of the one characteristic that can be stated: the underlying probability of DCS (P(DCS)) for a given exposure.

The most successful mathematical model uses a risk function (also known as a hazard or survival function) to describe the instantaneous rate of probability of DCS occurrence (16). As shown in Equation 1, the instantaneous risk r,

$$r = \sum_{i=1}^{n} r_i = \sum_{i=1}^{n} A_i \frac{P_{tis_i} - P_{amb} - P_{thr_i}}{P_{amb}}, \text{ where all } r_i \geq 0 \qquad (1)$$

is proportional to the relative "gas supersaturation" in each of the n kinetic compartments (tissues). Here, $Ptis_i$ is nitrogen tissue tension in *i*th compartment or tissue, P_{amb} is ambient pressure, $Pthr_i$ is the risk-free supersaturation threshold, and A_i is a scale factor. The non-negativity restriction avoids the unphysical condition of "negative risk."

Following the formalism of risk functions, the overall probability of DCS occurrence, P(DCS), depends upon the integral of instantaneous risk, r, up until time T, as seen in Equations 2 and 3.

$$P(S)_T = e^{-\int_0^T r\,dt} \tag{2}$$

$$P(DCS)_T = 1.0 - P(S)_T \tag{3}$$

where P(S) is the survival (or safe from DCS) probability.

For a real time decompression meter, it is very desirable to have an algorithm proven as reliable in short time periods. In 1992 we described how the time course of the risk function can be calibrated by fitting to data where the time of occurrence of DCS is well documented (12). In that same time period we presented a set of over 4000 very well documented experimental dives for which the profiles and outcomes were known, and where the time of occurrence of over 200 full and marginal cases of DCS were detailed with a precision that ranged from minutes to hours (17). (Marginal cases are decompression-related adverse outcomes that do not require recompression therapy, but are valuable to assist modeling. [10]) The model of equation (1) was fitted to most of these data (16). The model

was shown to have excellent predictive abilities in a subsequent trial of 700+ dives (18), which emphasized the variable depth and repetitive dives anticipated to stretch the use of a decompression computer. The model was then updated and chosen for real time implementation. Model parameters are given in Appendix 1, Table 4.

For any given dive (depth and decompression time history), the model (including the fitted parameters) can be used as a "black box" to estimate risk of DCS, (P(DCS)), as shown in Figure 1A. However the model does not directly provide an optimal decompression schedule (Figure 1B), which we define as the schedule requiring minimum total stop time (TST) such that the diver's risk of DCS (P(DCS)) is less than a specified acceptable level. Note that "optimal" schedules also require additional constraints to be defined such as stop depths, stop time increment, specified maximum rate of ascent, etc.

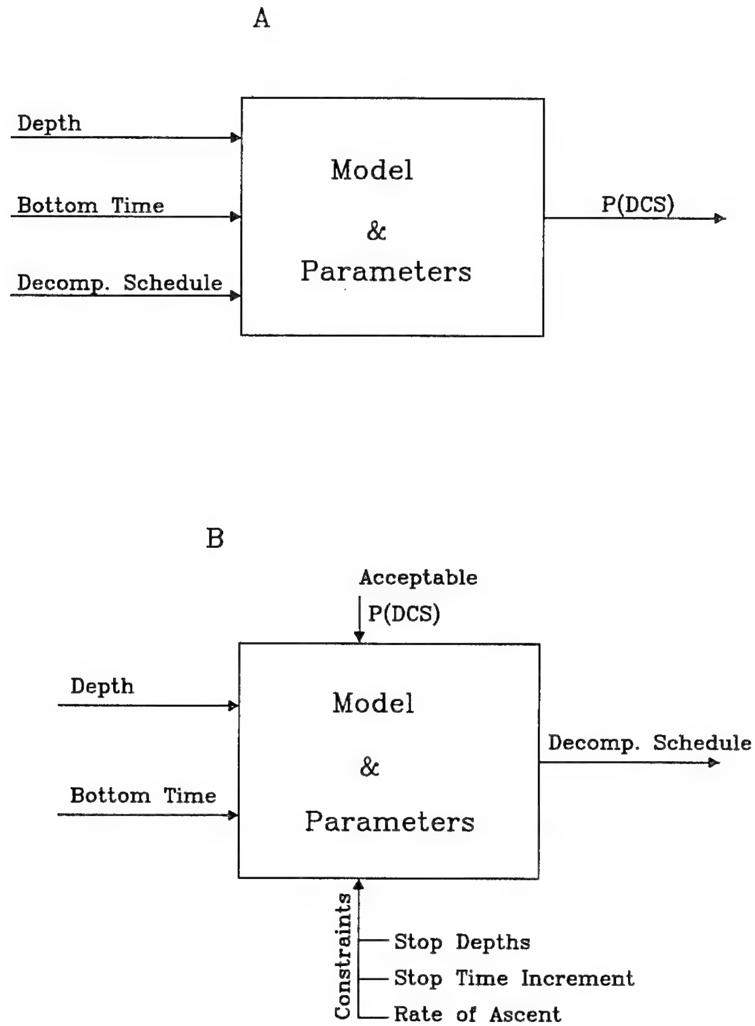


Figure 1. In sketch A the probabilistic model and its parameters constitute a reliable "black box" that evaluates the overall safety of a complete dive profile. Sketch B shows desired use of the box to produce an optimal decompression schedule for a partially completed dive subject to additional procedural constraints.

A direct mathematical solution for this problem does not exist. An optimal schedule can only be found by searching a number of possible decompression paths. A complete global search is impractical due to the large number of possible decompression paths. For example, 200 min of decompression time distributed across 5 stop depths in 10-minute increments leads to 10,626 search combinations in finding the safest combination (19). An optimized semi-global search method can reduce the search by an order of magnitude (19). Still, such an approach of evaluating hundreds or thousands of possible schedules in real time is prohibitive without an unrealistically fast computer to be carried by an individual diver.

This paper describes a method that allows computing an optimal decompression schedule (with minimum total stop time, TST) with an acceptable risk or P(DCS) level (R_{acc}), in real time. In practice, a new optimal decompression schedule is provided to the diver at regular and frequent time intervals (1-10 second update cycle) as she travels up and down in the water.

REAL TIME ALGORITHM

Initialization

At the start for a "clean" diver (one who has not been diving for 2 days or more), the three tissue compartments of the model (16) contributing to equation 1 are considered to be saturated at 1 ata on air. The starting TST is zero minutes.

No-Decompression Status

As the diver descends through the water, she will at first have accumulated only a negligible amount of inert gas, and therefore be in a no-decompression (NoD) status. To

check for the NoD status, risk is calculated, as shown in Figure 1a, for a test profile that has the diver immediately returning to the surface at the prescribed rate and then staying on the surface. If the computed risk is less than the acceptable level of P(DCS), R_{acc}, the diver remains in a NoD status.

The diver will be interested in knowing the amount of time remaining before she can no longer return directly to surface. This is called the remaining no-decompression time (RNDT). The RNDT is calculated by repeated use of the "black box" in Figure 1a. The RNDT is found by constructing subsequent test profiles by assuming some additional time at the current depth before returning to the surface. At some amount of added bottom time the proposed test profile will exceed the R_{acc}. The longest of these proposed bottom times that does not exceed the R_{acc} is the RNDT.

The RNDT found is only valid for the current time and depth, so a new RNDT must be calculated at each update cycle. Since both time and depth do not change very much by the next time interval, the previous RNDT can be used as a starting point to find the current RNDT. Usually only a few trial profiles need to be examined before the RNDT is known to desirable precision, for example, 1 minute.

Decompression Stops Required

There will come a time during a dive when immediate surfacing will be riskier than the R_{acc} and the diver will need some decompression time when she does ascend to the surface. If, for example, we accept a constraint that the search for the optimal decompression schedule will use a minimum 5-minute increment of stop time, we would need to search for the optimal placement of the 5-minute stop time. That is, at what depth would the 5-minute

stop time provide the greatest benefit. Choice of depths to consider is another constraint. We follow common practice of using multiples of 10 feet as stop depths.

As the diver stays at depth even longer, the 5 min of stop time may not be enough, requiring at least an additional 5 min. With more than the minimal 5-minute stop, the true globally optimal decompression schedule could be obtained by searching all possible combinations of distributing the 10 or more minutes of TST over all possible stops in 5-minute increments. Examining all combinations will get prohibitively long as TST gets longer, e.g., distributing 10 min of TST over 4 stop depths in 5-minute increments leads to 10 combinations, whereas 30 min of TST leads to 84 combinations. The process quickly builds to thousands of possibilities.

Rather than search the full set of possibilities, we instead only search "near" the prior optimal schedule. The optimal placement of an additional 5 min is only considered by adding to the old optimal schedule. This reduces the number of required searches to the number of stop depths under consideration. For example, let us assume that the previous optimal schedule consists of 25 min of TST with stop times distributed as 15, 5, and 5 min, at 10, 20, and 30 feet of sea water (fsw), respectively; this schedule no longer satisfies the acceptable risk criterion. That is, if the diver used this schedule to arrive at surface, her risk of DCS would be greater than R_{acc}. The local search consists of adding 5 min to the previous schedule by placing the additional 5 min at each of the depths (10, 20, 30 fsw), as well as the next deeper depth of 40 fsw, and comparing the corresponding projected risks as illustrated in Table 1.

Table 1. Local search for a longer schedule							
			Stop Time (min)			Projected	
STOP DEPTH (fsw)	**40**	**30**	**20**	**10**	**TST**	**P(DCS)**	
Previous Schedule		5	5	15	25	0.0502	*
Local Search 1	0	5	5	**20**	30	0.0495	
Local Search 2	0	5	**10**	15	30	0.0493	*
Local Search 3	0	**10**	5	15	30	0.0499	
Local Search 4	**5**	5	5	15	30	0.0498	

The above example, where R_{acc} is set to be 5%, shows that when the previous schedule is used the projected risk is greater than R_{acc}. Four longer schedules are examined and the optimal schedule (lowest P(DCS)) is found to be the one with additional 5 min at 20 fsw. Thus, the total number of schedules (including the previous schedule) that need to be examined is N+2, where N is number of stops for the previous schedule. This, of course, assumes that at least one of the proposed longer schedules satisfies the R_{acc} criterion.

The diver may need a shorter decompression schedule than her previous optimal one. This would require that shorter schedules, with 5 min less TST, also be examined as shown in Table 2.

Table 2. Local search for a shorter schedule							
			Stop Time (min)				
STOP DEPTH (fsw)	**40**	**30**	**20**	**10**	**TST**	**Projected P(DCS)**	
Previous Schedule		5	5	15	25	0.0486	*
Local Search 1		5	5	**10**	20	0.0495	
Local Search 2		5	**0**	15	20	0.0498	
Local Search 3		**0**	5	15	20	0.0493	*

When the previous schedule is examined, the projected risk is found to be lower than R_{acc}. One could at this point just use the previous schedule as the optimum. But further examination of all possible shorter schedules reveals that the one with no stop time at 30 fsw has the minimum projected risk and still meets the R_{acc} criterion. Local Search 3 then becomes the new optimal schedule. If the shorter schedules were all riskier than the acceptable level, the previous schedule would have been declared as the optimal one. This path for the shorter schedule would need N+1 schedules to be examined. Thus, either the shorter or the longer schedules are explored during any update cycle depending upon the projected risk of using the previous schedule, leading to a maximum of N+2 searches.

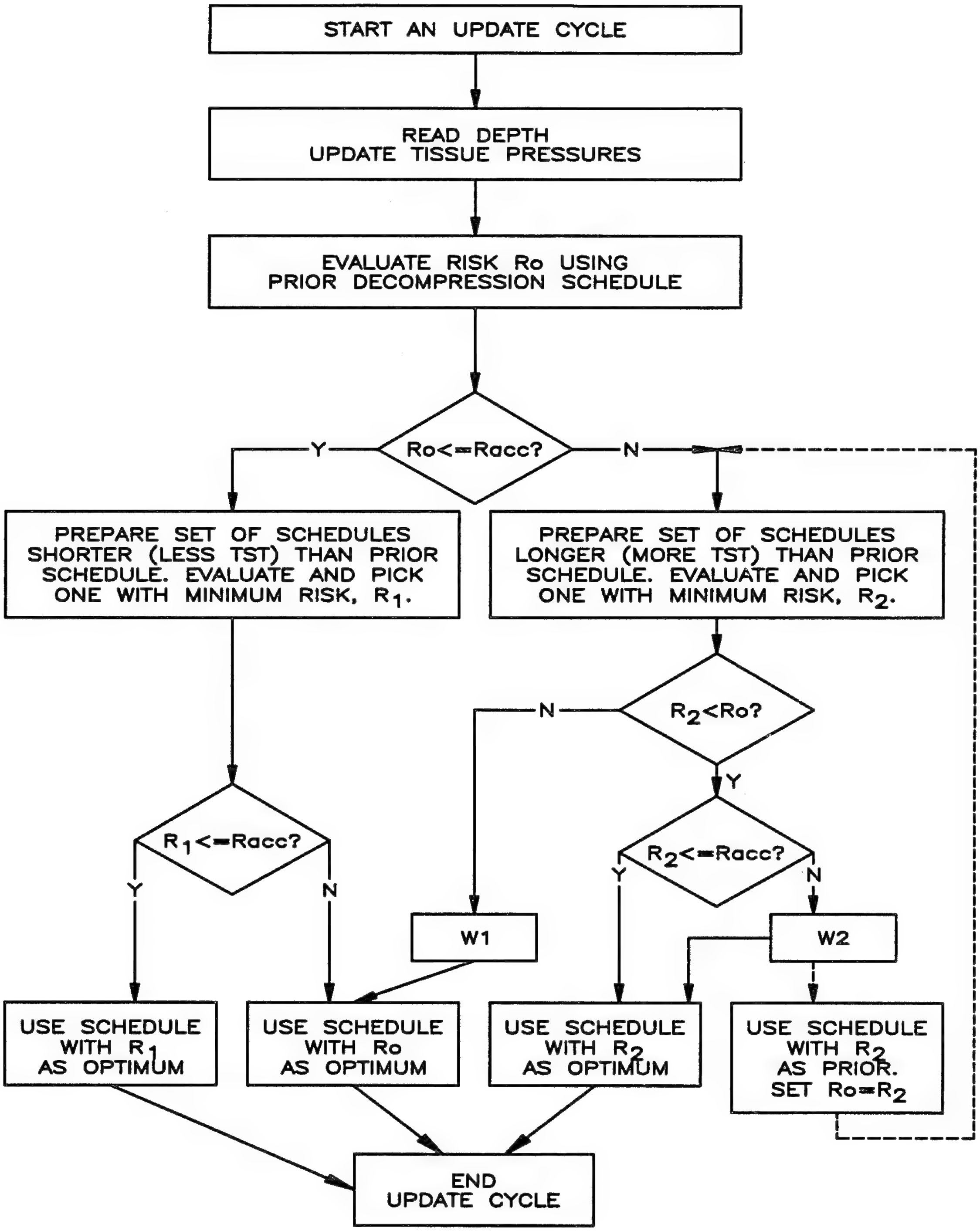


Figure 2: A block diagram of an update cycle.

Figure 2 shows the paths that could be followed during an update cycle. At the start of an update cycle, the diver's current depth is sensed, the three tissue pressures are updated to that depth, and the previous schedule is evaluated. A path for examining either the longer or shorter schedules is then taken depending upon how risky the prior schedule was. The longer TST path (right side of Fig. 2) may lead to some problems. Condition W1 arises from the longer schedules actually being riskier than the prior schedule. This can occur if R_{acc} is set so low that just the travel between stops can be of greater risk than R_{acc}. Longer schedules can actually increase this risk due to gradual saturation at each stop depth. Therefore, longer schedules without benefit are not used and the prior schedule is kept as the optimal one.

Condition W2 arises when one stop time increment improves safety, but not enough to satisfy the R_{acc} criterion. Two choices are possible. The first is to accept the better, yet inadequate schedule, and hope that subsequent update cycles will "catch up" and find an optimal schedule (path in solid line from W2). Computational limitations may allow no other choice. The second choice, (path in dashed line from W2), is to use the better but inadequate schedule with R2 to explore another incremental stop time.

ALGORITHM PERFORMANCE

Optimality

How well does this algorithm provide a truly optimal result? Results in the NoD range are not in question since only a single result is needed, and calculation is direct. Beyond that range, we chose to examine 152 decompression schedules over the desirable full

range for compressed air diving: depths ranging from 30 fsw to 200 fsw, and bottom times from several minutes up to 720 min. Constraints were chosen to be of practical interest: acceptable level of risk was set to 5%, stop time increment (the search grid) set to 5 min, stop depth increment set to 10 fsw, update cycle time for the local search method set to 10 s. The results of the local search algorithm described above were compared to the much more intensive semi-global search approach (19). A slight difference in the latter method was a stopping risk tolerance criterion of 0.001%, so that the final decompression chosen could have a risk as high as 5.001%. (The local search always finds one with a risk LOWER or equal to R_{acc}.)

The TSTs for these 152 dives ranged from 5 min to 3545 min; with 96 dives having TSTs longer than 300 min. For 150 dives, results of the two methods were within 5 min of having identical TST. Only 2 dives out of 152 lead to 10 min longer TST by the local search method. The TSTs for these 2 dives by the semi-global search method were in fact greater than 1860 min, making the 10-minute difference insignificant. The TSTs by the local search method were always longer than those by the semi-global method, whenever the difference existed.

Some small differences were also found in the distribution of times across different stop depths. The two methods agreed within 5 min at all stops for 108 of the 152 schedules. The TSTs for these 108 schedules ranged from 5 min to 3475 min. The remaining 44 schedules, with more than a 5-minute difference somewhere in the stop time distribution, were all longer than 380 min in TST. For very long schedules, the stop time distribution by the two methods can in fact look quite different even if the TSTs are within 5 min of each

other.

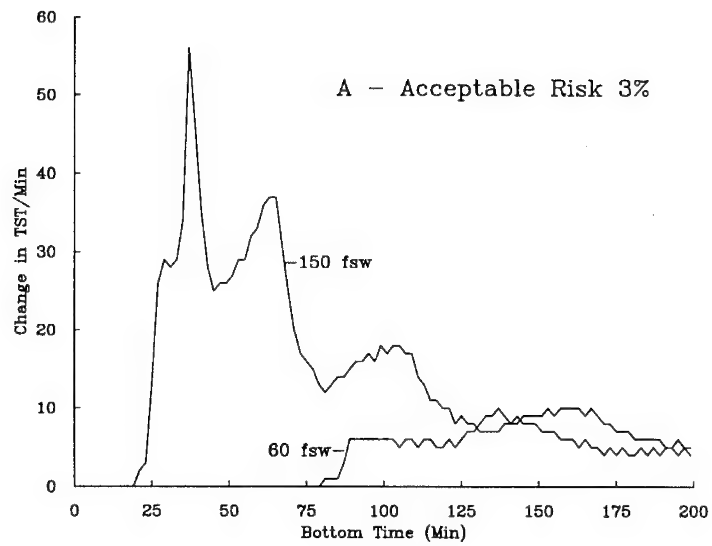
This difference between actual schedules arises due to mainly two reasons. First, P(DCS) as a function of stop time distribution with same TST is extraordinarily flat in many regions, i.e., many stop time distributions with the same TST lead to almost same P(DCS) and are essentially equally optimal. That observation underlies much of the current approach of viewing 5 min as a minimally important time for exploration of decompression schedules. The second reason is that even the semiglobal search (19) does not examine all possible combinations of the stop time distribution, and thus may in fact occasionally lead to a slightly non-optimal stop time distribution. Overall, the local search appears to lead to a safe and usually optimal schedule much faster than any previous method.

Timing Considerations

The present algorithm is substantially more demanding on computational resources than deterministic models, and some discussion of timing requirements is worthwhile. Sampling, calculation and updating is performed in cycles. The update cycle time is the time required to sense the diver's new depth and perform all calculations necessary to find a new optimal schedule. Specification of the best update cycle time is not obvious. "The fastest cycle time possible" is an easy answer if computational resources are unlimited. If the processor being used is very slow and takes a very long time (e.g., 2 min) for searching just a few schedules, one needs to answer whether 2 min is fast enough.

The answer to how fast we need to cycle depends upon how quickly the TST changes as result of staying at the current depth an additional length of time, i.e., the first derivative of TST with respect to bottom time, D = d(TST)/d(Bottom time). This derivative depends upon

depth and R_{acc}. Figure 3A shows the change in TST in minute per minute of bottom time for 150 and 60 fsw dives where the R_{acc} was set to 3%. Fig. 3B is the same except for the R_{acc} being set to 5%. The figures were generated by incrementing bottom time by 2 min and calculating TST in 2-minute increments. The peaks arise from a complex interplay of risk contribution of each of the three tissue compartments with the optimal search strategy in trying to minimize the total risk. The jagged appearance at the later times corresponds to times when a new 2-minute increment needs to be added to TST. All plots eventually will return to zero when tissues saturate and TST remains constant. It is obvious from these and similar plots that deeper depths lead to a higher derivative, and that lower R_{acc} (more conservative schedules) also leads to a higher derivative.



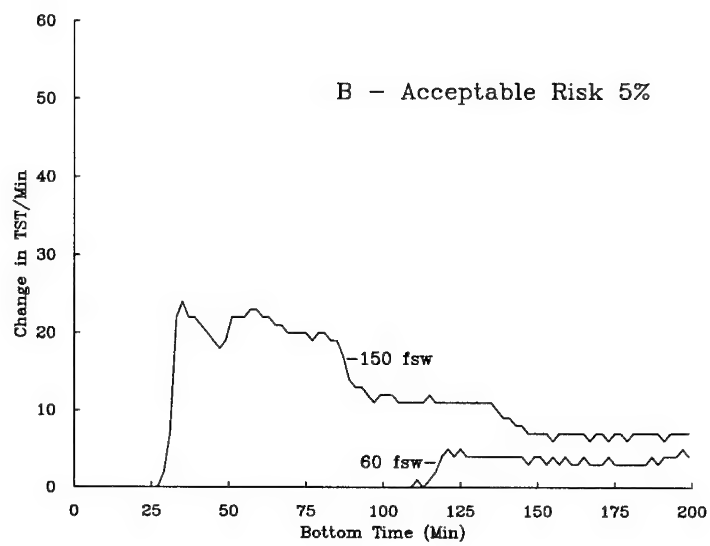


Figure 3. Plots of derivative D: change in TST with respect to bottom time.

Larger values of derivative, D, denote regions of rapid TST increase and hence greater computational requirements. If the decompression meter's processor speed is limited, the local search should be kept at a minimum, which means that the update cycle rate should be such that the processor can find the optimal schedule within one stop time increment. Any longer update rate would lead to searching for schedules requiring multiple stop time increments and requiring longer computation time, and the processor may never keep up with the calculations. That means the following condition has to be met:

$$C \leq 60 * \text{TIMINC} / D_m \tag{4}$$

where C is update cycle rate in seconds, TIMINC is the stop time increment (or the search grid) in minutes and D_m is the maximum value of the derivative d(TST)/d(Bottom time) in min/min. Since D_m depends upon depth and R_{acc}, as shown in Figure 3, we have to specify the working environment of the system and compute a maximum value of D_m under such conditions. For example, if the real time algorithm is to be used in shallow water alone where maximum D_m does not exceed 10 min/min for a specified R_{acc}, then the update cycle time can be as slow as 30 seconds using a stop time increment of 5 min.

If the processor speed is not the limiting factor, then the update cycle time is not so critical, since the local search strategy can be extended to multiple stop time increments to cope with a large D_m (This case is represented by condition W2 followed by dashed line path in Fig. 2). In such a case, other operational considerations will dictate the cycle time, e.g., how often other monitoring functions need to be performed, or how to extend life of the battery.

In practice there is an alternative to finding D_m and Equation 4 to establish a satisfactory cycle time for a given operational envelope, by using the basic real time algorithm. In Fig. 2, box W2 indicates that adding one stop time increment to the prior TST is not sufficient, and therefore signals a computationally limited condition. Simulation of the most taxing part of the operation (deepest depth, lowest R_{acc}, mid to long times) with a set of possible update cycle times will eventually lead to condition W2. The longest simulated cycle time avoiding W2 then sets the necessary processor speed: one needs to choose a processor capable of computing N+2 decompression schedules within the cycle time. (Here N is the maximum number of stops required under the simulated worst case scenario.)

SPECIAL FEATURES

Calculations During Decompression

When using printed decompression tables, the start of decompression is the end of any flexibility, and divers control their stop depth and times as carefully as possible. That approach could be carried into computer use also. At the end of bottom time, when the diver starts ascending, one could simply cease examining new schedules and preserve the last prescribed solution for the diver to follow. In practice it would be difficult to automatically determine the condition upon which no further calculations are necessary. Moreover, this approach would be restrictive since it would assume the diver intended to complete the decompression without deviation. Additional logic would be needed to resume calculations, if the diver intentionally or otherwise, strays from the prescribed solution.

Another approach would be to continue updating new decompression possibilities throughout the dive, including the ascent. The optimal decompression path can, in fact, change due to slight variations in the diver's actual depth as compared to the prescribed decompression path. Some schedules, during an ascent, could suddenly reduce the anticipated remaining stop time while the diver is at a stop. If this is considered an undesirable surprise it can be avoided by "freezing" the stop time of the decompression stop depth once the diver arrives at that depth. "Frozen" stop time is achieved by not examining schedules that make a change to the time at the current stop depth. Adjustments can continue to be made to the shallower stop times. Once the shallowest stop depth is reached, for example 10 fsw, no further adjustment is made.

Conditional Probability

The acceptable risk level in a dive can be implemented in several ways depending on risk management decisions. The most practical choice implements conditional probability, which refers to the probability of a future event, given that no event has occurred up until the present moment. For illustration, Figure 4 shows a dive profile with corresponding tissue inert gas pressure for one compartment. The shaded areas R1 through R4 are the areas of supersaturation and thus risk accumulation. If the diver is at point T1, her projected decompression path would involve the risk total of all shaded areas R1 through R4.

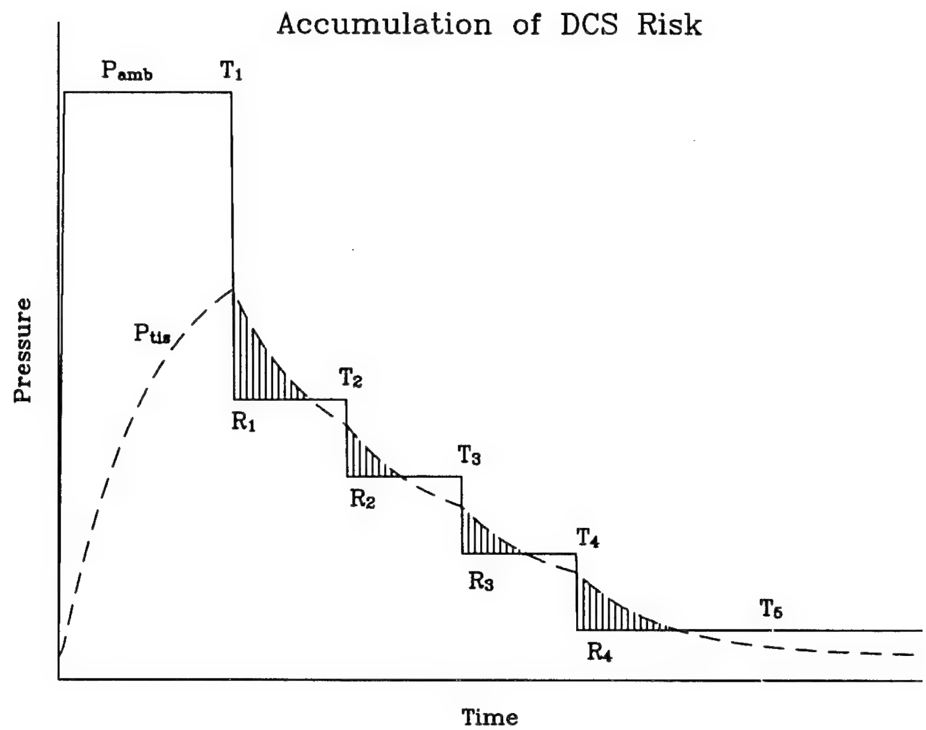


Figure 4. Schematic dive profile showing ambient pressure (solid line), tissue tension of a compartment (dashed line), and intervals of risk accumulation according to Equation 1 (vertically hatched areas R1-R4).

As the diver proceeds to decompress she will arrive at point T2. The shaded area before time T2 (R1) is the risk already incurred by the diver, whereas the shaded areas after T2 (R2 through R4) would be the risk involved in future if the diver were to follow the rest of the profile. The risk already incurred plus the future risk would be the total risk the diver would incur for the entire dive. If the diver does complete the dive and is at point T4 and has not shown any symptoms of DCS then her chance of yet suffering from DCS would be proportional to the risk into the future, i.e., proportional to the last shaded area R4.

One can see clear advantage in the use of conditional probability for repetitive diving. For example, if the diver is at a point T5 in Figure 4, i.e., has already completed the previous dive, and if the total incurred risk on the first dive is equal to R_{acc}, the additional risk due to the next dive would always put her total risk over R_{acc}, and she could never surface from the second dive with total risk less than R_{acc}. Using conditional probability the diver disregards the incurred risk and only manage the future risk. This corresponds to a policy of accepting the same chance of DCS on the next dive as on the prior dive. The lifetime risk, of course, increases steadily with increasing diving activity (12).

With continuous implementation of conditional probability, the decompression schedule may get shorter during the present dive. For example, when the diver is at point T1 in Figure 4, the optimal schedule is such that her future risk, which is almost equal to R_{acc}, includes all of the shaded areas R1 through R4. During her ascent, at point T2, the risk incurred in the past (R1) would be disregarded and a new optimal decompression schedule would be computed such that her future risk at this point, areas R2 through R4, is equal to R_{acc}, thus allowing the new decompression schedule to get shorter. By the time she arrives at

the surface, the diver's total risk would be higher than R_{acc} and her actual decompression schedule (conditional schedule) would be shorter than the one anticipated at the end of bottom time (nonconditional schedule). If the technique of "freezing stop time" is used, then the difference between the conditional and nonconditional schedule is reduced.

The quantitative implication of conditional implementation of schedules combined with frozen stop times was examined with the same simulated 152 different dives discussed earlier. The conditional TSTs were shorter by an average of 12.7 min (range 0 to 45 min) for the dives with nonconditional TST of 300 min or less. Total P(DCS) for these conditional schedules increased on average by 0.0018 for the same dives, i.e., on average the total P(DCS) for the conditional schedules was 5.18%.

When schedules with TST longer than 5 h were examined, the conditional+frozen schedules were shorter by 161.6 min (range 0 to 385 min) than the corresponding nonconditional schedules. The reduction in TST for these long dives amounted to 14.4%. The average increase in total P(DCS), for these schedules, was found to be 0.0095, i.e., on average total P(DCS) for the conditional schedules was 5.95%.

Variable Acceptable Risk

Several well known decompression tables do not apply the same level of conservatism for all types of dives (20). Generally, NoD dives and the dives requiring short TSTs are conducted more conservatively, i.e., with a lower value of acceptable risk level. But if the same level of conservatism were applied to the longer dives, the TST requirement would become impractically long. Table 3 shows a sample of TST requirements for some moderate to severe dives when R_{acc} is set at different levels. For example, it may be desirable to set

Table 3. TST requirement for constant depth dives with R_{acc} set at different levels

Depth (fsw)	Bot (min)	TST (min) R_{acc} 2 %	3 %	4 %	5 %	7.5 %	10 %
50	120	145	25	0	0	0	0
50	240	900	570	365	230	75	0
60	60	5	0	0	0	0	0
60	120	590	210	105	25	0	0
60	180	940	600	380	245	85	0
90	30	5	0	0	0	0	0
90	60	525	180	75	10	0	0
90	120	1495	935	685	495	260	130
120	20	5	0	0	0	0	0
120	40	530	180	75	10	0	0
120	80	1680	1050	770	575	315	185
150	15	5	0	0	0	0	0
150	30	555	180	75	15	0	0
150	60	1800	1160	845	645	360	225
180	10	0	0	0	0	0	0
180	20	160	40	5	0	0	0
180	40	1400	890	635	445	245	110

R_{acc} at 2% for a 90-fsw dive with a 20-minute bottom time. But the same obligatory R_{acc} will be impractical when bottom time gets longer. Many feel that 2-3 h decompression in the water creates serious additional hazards in itself. Thus, some form of variable acceptable risk level would be desirable.

One possible solution would be to make the acceptable risk level rise with bottom time. But a satisfactory bottom time rule would have to be depth-dependent as well, since even several hours at shallow depths do not incur much TST requirement. A serious practical drawback in this method involves identifying what constitutes "bottom time and depth" in the freely maneuvering up and down mode desired in a real time device.

Another solution would be to make the acceptable risk level a function of the TST with specifications as shown in Figure 5. For NoD dives and dives with very little TST up to TST_L, the low conservative value of R_{LOW} is used as the acceptable risk level. More severe dives requiring longer TST allow the acceptable risk of DCS to rise. The rise can be unbounded or, as illustrated in Figure 5, can stop at a some maximum risk of R_{HIGH} when TST reaches a value of TST_H. A reasonable choice, for example, could be R_{acc} rising linearly from 2% to 5% over the TST range of 20 to 60 min.

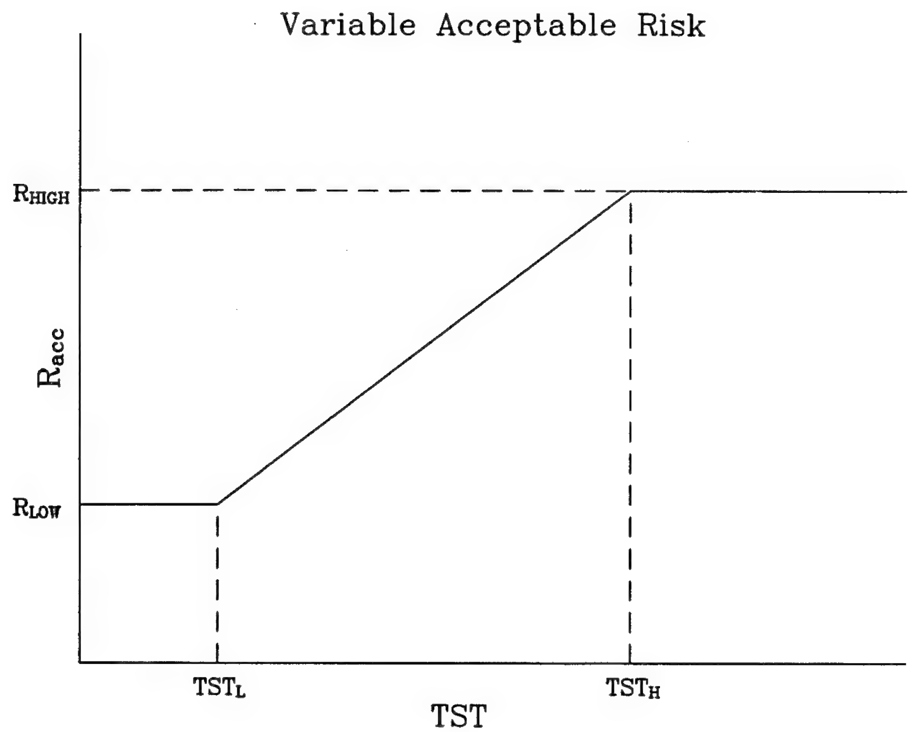


Figure 5. Conceptual diagram of variable acceptable risk implementations with R_{acc} rising with TST.

The TST-R_{acc} linkage design may lead to an oscillating TST. An increase in TST causes the acceptable risk level to rise, which, in turn, causes the TST to decrease. Another problem is encountered during decompression as the remaining TST decreases. Should the value of R_{acc} decrease accordingly? A straightforward decrease of R_{acc} will counteract the whole purpose of having the variable acceptable risk. For example, at the time of arrival back at the surface, the TST would be zero and R_{acc} would have decreased to R_{LOW}, thus leading to a low value of the conditional risk when a higher one was desired. As a result, the decompression stops would have become much longer than desired.

Both problems are avoided by allowing R_{acc} only to increase with increasing TST, but never to decrease until the TST is reduced to zero <u>and</u> the diver is at the surface. When the diver surfaces after a dive with zero TST, the R_{acc} is allowed to decrease as the diver's future risk decreases. For example, again referring to Figure 4, let us assume that the diver is at point T1 and the value of R_{acc} has reached R_{HIGH} because of a long TST requirement, then during decompression the value of R_{acc} is kept at R_{HIGH}. With application of conditional probability her future risk during decompression will be almost equal to R_{HIGH}. When she arrives at the surface (just after T4), her future risk will be equal to R_{HIGH}, which is equal to the last shaded area R4. (If the technique of "freezing stop time" is used, the future risk will be somewhat less than R_{HIGH}). As she spends time on the surface, her future risk will decrease, and the value of R_{acc} will decrease accordingly. Subsequent repetitive dives will start with R_{acc} set to the future risk level at the time of the next dive. Eventually the instantaneous risk in Equation 1 will approach zero and R_{LOW} will be regained.

Multiple Breathing Gas Mixes

The algorithm can be modified to allow the diver to use two or more gas mixture supplies. For example, compressed air could be the primary gas and a second supply, relatively enriched in oxygen, could be available (7). The second source might be unsuitable for the entire dive because of limited supplies or from a concern for oxygen toxicity if used at deeper depths. In general, the diver might switch to the alternate gas supply at any time. To be prepared for a sudden switch, a separate optimized schedule is prepared for each gas mix. The computational resources increase with the number of gases: that is, optimizing schedules for two gases requires about twice the calculations as for only one.

Different gas supplies lead generally to different TSTs. If a variable acceptable risk strategy that is dependent upon TST is used as shown in Fig 5, it creates another dilemma. If R_{acc} for each gas mix is allowed to vary according to its own TST, we may experience a paradox. Here the value of R_{acc} for the oxygen-rich mixture may be lower (safer dive option) and breathing the oxygen-rich gas could then result in a longer TST than that for air at some point in the dive. Whereas, if R_{acc} for each gas mix is forced to vary according to TST for air, then the oxygen-rich mixture will have shorter TSTs (faster dive option). Choices could be resolved depending on the purpose of gas switching.

IMPLEMENTATIONS

A PC-based dive planner was developed using the real time algorithm. It is intended for operations where real time control is not possible, but good records are kept of the divers' depth-time history. Late in the dive when only the decompression is needed, the profile is

loaded, and run by simulation in faster-than-real-time, until an appropriate decompression is in hand. The dive planner was approved by NAVSEA for the Naval Special Warfare use (21). The specifications on the planner are given in Appendix 1.

A real time system, using the algorithm, was developed and successfully used during human dive trials conducted at NMRI and NEDU in 1991 and 1992 (18). The dives were conducted in pressure chambers, which were manually controlled according to the decompression advice given by the algorithm. The system was implemented on a Micro-VAX 3800 (or Micro-VAX 3400), with an update cycle time of 5 s, conditional probability, the "freezing stop time" technique, TST-dependent variable acceptable risk level and up to three gas mixes with increased safety as the gas switching strategy.

The VAX experience proved that the algorithm is workable in an underwater decompression meter (UDM), given that the UDM's processor is fast enough. If the processor cannot finish computations within the required update cycle time, there are a few possible solutions. According to Equation 4, increasing the stop time increment, TIMINC, will provide longer update cycle time C, thus providing more time for computations. Restricting the UDM use only to shallower depths will decrease the value of maximum derivative D_m, and increase the update cycle time C, resulting in more time for computations.

Another solution could be to find ways to speed up the risk calculations since most of the processor time is spent in evaluating the risk of projected decompression profiles. A large fraction of processor time is spent evaluating that portion of the projected profile when depth changes with time, i.e., during ascent. Mathematics in the model were developed and programmed to deal with linear ramps in depth over time. Within the solution an iterative

method is used to find roots of the risk function. One way to increase the overall speed is to approximate the profile as a series of step changes in depth, and calculate that risk portion in single precision rather than double precision. The step approximation can be implemented two different ways. The simpler way would involve using a single step to get from the bottom depth to the first stop, while a more complicated way would use a "stair step" approach. We implemented the "stair step" simplification and tested it on VAX 4000 by generating a decompression table comprising of 1602 depth and time combinations. The original full-fledged version of the algorithm (in double precision with ramp treatments of depth changes) needed 18 h and 22 min while the new simplified version only took 3 h and 33 min to generate the same decompression table. When the TSTs according to the new method were compared to the original set, 1430 schedules had the same TST, 24 schedules had 5 min shorter TST, 144 schedules had 5 min longer TST, and 4 schedules had 10 min longer TST.

There are other ways to speed up the risk calculations. The risk evaluation involves numerous evaluations of the exponential function. It is possible to use a pre-calculated exponential lookup table and interpolate exact values, but effect on speed and accuracy would have to be evaluated.

For many applications and many available processors, no further simplifications are needed. The full algorithm was originally written in FORTRAN and used at 100+ times faster than real time. It has been converted to C+, and shown to run faster than real time in simulations on many small processors. For a relatively taxing condition (N=4 decompression stops, and 3 available gas mixtures), faster than real time has been obtained on several intel-

486 and 386 machines.

CONCLUSIONS

Only in the last 10 years has an objectively calibrated model been available to estimate the risk of DCS. During that interval, models have evolved to behave well across most of the range where nitrogen is the gas of concern (models are not yet available to work well when divers breathe substantial amounts of oxygen or helium). Computational hardware with greater power at lower cost has also been a hallmark of the last ten years. With the algorithm described here, well verified decompression models can now be used by individual divers in an extremely versatile manner. This marks an important plateau in decompression research development.

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GLOSSARY

Acceptable risk (R_{acc}):	The value of P(DCS) allowed by the diver or her sponsoring organization.
Algorithm:	A sequence of specific computational steps necessary to obtain specific quantities
Clean:	A state of a diver wherein her starting tissue nitrogen is well equilibrated with 1 atmosphere
Compartment (tissue):	A hypothetical portion of the diver's body having nitrogen uptake and elimination kinetics as described by a specific set of kinetic parameters.
NoD (No decompression, a status):	Condition during diving when no decompression stops are required by the diver; direct ascent to the surface is allowed.
Profile:	A sequence of depths over time that will lead to a prolonged stay at the surface. Profile may be an actual record, or may be a projection of one possible decompression path.
RNDT:	Remaining No Decompression Time; the time that a diver may stay AT THE CURRENT DEPTH without incurring an obligation for decompression stops.
Schedule:	Also Decompression Schedule. A full set of decompression stops and times to allow acceptably safe return of a diver to the surface after a specific dive.
Stop:	Also Decompression Stop. A prescribed depth at which the diver is required to remain for some time (the stop time) in order to continue a specified safe ascent to the surface.
Tissue:	See compartment.
TIMINC:	The minimum time interval considered for a decompression stop; typically 5 minutes.

TST:	Total stop time. Cumulative time required at all decompression stops for safe ascent to the surface.

Appendix 1: Dive planner specifications

The dive planner is implemented using variable risk strategy as shown in Fig. 5. The acceptable risk is set to 2.3% (R_{LOW}) at the start of a dive. When TST reaches 20 min (TST_L) the acceptable risk is linearly increased to 5% (R_{HIGH}) until TST reaches 60 min (TST_H), beyond which the acceptable risk is kept constant at a 5% level. The planner allows use of two breathing mixes: air and 0.7 ATA constant PO_2 in N_2. The acceptable risk for computing schedules for the second gas (0.7 ATA PO_2) changes according to air TST (faster dive option).

Table 4. Model parameters

Parameter	Tissue 1	Tissue 2	Tissue 3
Time constant α (min)	1.78 ± 0.84	60.32 ± 18.58	515.77 ± 36.85
Pxo (fsw)	∞	0.98 ± 0.74	∞
Pthr (fsw)	0.0	0.0	2.26 ± 0.6
Scale Factor A	3.2E-3 ± 2.3E-3	0.11E-3 ± 0.037E-3	1.1E-3 ± 0.16E-3

Parameters for the model in the Equation 1, as implemented in the dive planner, are given in Table 4. There are 3 kinetic compartments or tissues (n=3) in the model. Parameters α and Pxo define the nitrogen tissue tension Ptis for each tissue (16). Parameter α is the time constant for nitrogen uptake. Pxo determines the shape of nitrogen washout in a compartment. When Ptis exceeds the value Pamb + Pxo, nitrogen washout is delayed by switching to linear kinetics. The nitrogen washout switches back to exponential kinetics as soon as Ptis drops below Pamb + Pxo. Thus, when Pxo is set high (∞), Ptis never exceeds the term Pamb + Pxo and washout always remains in an exponential mode (Tissues 1 and 3).